

This Briefing Has Been Approved
For Public Release

Resolution Metrics for Space-Based Imagery

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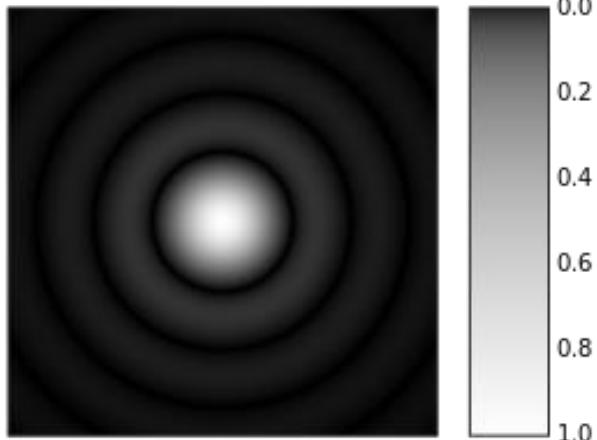
Overview of Presentation

- **Performance dimensions for VNIR/SWIR EO satellites**
 - *Spatial resolution* ←
 - *Spectral resolution* ←
 - *Temporal resolution and revisit time*
 - *Radiometric resolution and accuracy*
- **Panchromatic and MS/SS/HS Spatial Resolution**
 - *Implications of Discrete Image Sampling*
 - What is the Meaning of “Q”?
 - *The GRD versus the GSD*
 - *The PSF versus the Pixel Pitch (p)*
 - Pathways to 1.0m, 0.5m and 0.25m GSD: Variation of D, Q, and H
 - What are the implications of oversampling?
 - What are the implications of super-resolution?
 - *Spectral Imaging: the Design of Q for MSI and HSI Sensors*
 - *Signal-to-Noise (SNR) and Radiometry (Accuracy and Precision)*

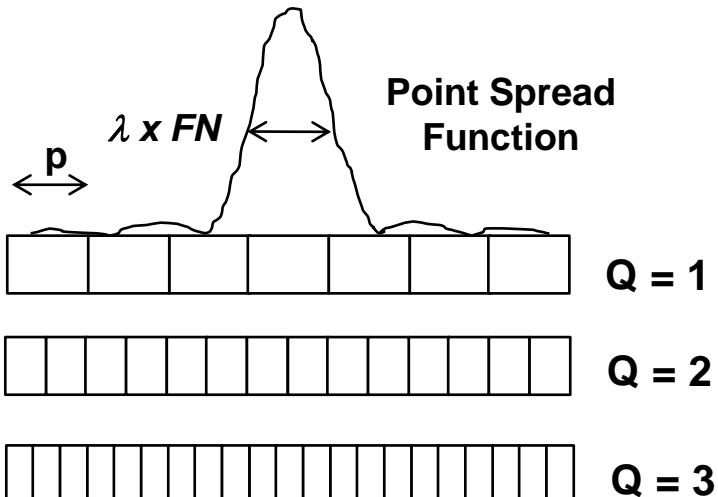


Panchromatic Spatial Resolution

Diffraction and Sampling Limitations for Point Sources



- **Diffraction-limited resolution**
 $GRD = 1.22 \times (\lambda/D) \times H$ (*Rayleigh criterion*)
- **Sampling-limited resolution**
 $GSD = (p/L) \times H = IFOV \times H$
- **“Q” is a property of the sensor only**
 $Q = (\lambda \times FN)/p$, $FN = L/D$
- **Q relates GRD and GSD**
 - $GRD = 1.22 \times Q \times GSD$
 - $Q = 2$ for Nyquist sampling (*best resolution*)
 - *Choice of Q is a critical design feature*



Pathways to Hi-Res PAN: Variation of D, Q, and H

Aperture D(m)	$\lambda_{\text{mean}} (\mu\text{m})$	Pixel Pitch p(μm)	Focal Length L(m)	Q ($\lambda \times \text{FN}/p$)	IFOV (μrad)	H (km)	350	400	450	500	550	600	650	700
0.35	0.675	8.00	3.32	0.8	2.41	GSD (m)	0.84	0.96	1.08	1.21	1.33	1.45	1.57	1.69
0.35	0.675	8.00	4.15	1	1.93		0.68	0.77	0.87	0.96	1.06	1.16	1.25	1.35
0.35	0.675	8.00	4.98	1.2	1.61		0.56	0.64	0.72	0.80	0.88	0.96	1.04	1.13
0.35	0.675	8.00	5.81	1.4	1.38		0.48	0.55	0.62	0.69	0.76	0.83	0.90	0.96
0.50	0.675	8.00	4.74	0.8	1.69		0.59	0.68	0.76	0.84	0.93	1.01	1.10	1.18
0.50	0.675	8.00	5.93	1	1.35		0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.95
0.50	0.675	8.00	7.11	1.2	1.13		0.39	0.45	0.51	0.56	0.62	0.68	0.73	0.79
0.50	0.675	8.00	8.30	1.4	0.96		0.34	0.39	0.43	0.48	0.53	0.58	0.63	0.68
0.60	0.675	8.00	5.69	0.8	1.41		0.49	0.56	0.63	0.70	0.77	0.84	0.91	0.98
0.60	0.675	8.00	7.11	1	1.13		0.39	0.45	0.51	0.56	0.62	0.68	0.73	0.79
0.60	0.675	8.00	8.53	1.2	0.94		0.33	0.38	0.42	0.47	0.52	0.56	0.61	0.66
0.60	0.675	8.00	9.96	1.4	0.80		0.28	0.32	0.36	0.40	0.44	0.48	0.52	0.56
0.65	0.675	8.00	6.16	0.8	1.30		0.45	0.52	0.58	0.65	0.71	0.78	0.84	0.91
0.65	0.675	8.00	7.70	1	1.04		0.36	0.42	0.47	0.52	0.57	0.62	0.68	0.73
0.65	0.675	8.00	9.24	1.2	0.87		0.30	0.35	0.39	0.43	0.48	0.52	0.56	0.61
0.65	0.675	8.00	10.79	1.4	0.74		0.26	0.30	0.33	0.37	0.41	0.45	0.48	0.52
0.70	0.675	8.00	6.64	0.8	1.21		0.42	0.48	0.54	0.60	0.66	0.72	0.78	0.84
0.70	0.675	8.00	8.30	1	0.96		0.34	0.39	0.43	0.48	0.53	0.58	0.63	0.68
0.70	0.675	8.00	9.96	1.2	0.80		0.28	0.32	0.36	0.40	0.44	0.48	0.52	0.56
0.70	0.675	8.00	11.61	1.4	0.69		0.24	0.28	0.31	0.34	0.38	0.41	0.45	0.48
0.80	0.675	8.00	7.59	0.8	1.05		0.37	0.42	0.47	0.53	0.58	0.63	0.69	0.74
0.80	0.675	8.00	9.48	1	0.84		0.30	0.34	0.38	0.42	0.46	0.51	0.55	0.59
0.80	0.675	8.00	11.38	1.2	0.70		0.25	0.28	0.32	0.35	0.39	0.42	0.46	0.49
0.80	0.675	8.00	13.27	1.4	0.60		0.21	0.24	0.27	0.30	0.33	0.36	0.39	0.42
1.10	0.675	8.00	10.43	0.8	0.77		0.27	0.31	0.35	0.38	0.42	0.46	0.50	0.54
1.10	0.675	8.00	13.04	1	0.61		0.21	0.25	0.28	0.31	0.34	0.37	0.40	0.43
1.10	0.675	8.00	15.64	1.2	0.51		0.18	0.20	0.23	0.26	0.28	0.31	0.33	0.36
1.10	0.675	8.00	18.25	1.4	0.44		0.15	0.18	0.20	0.22	0.24	0.26	0.28	0.31

$$\text{IFOV} = p/L = [\lambda_m / (Q \times D)]; \text{ GSD} = \text{IFOV} \times H$$

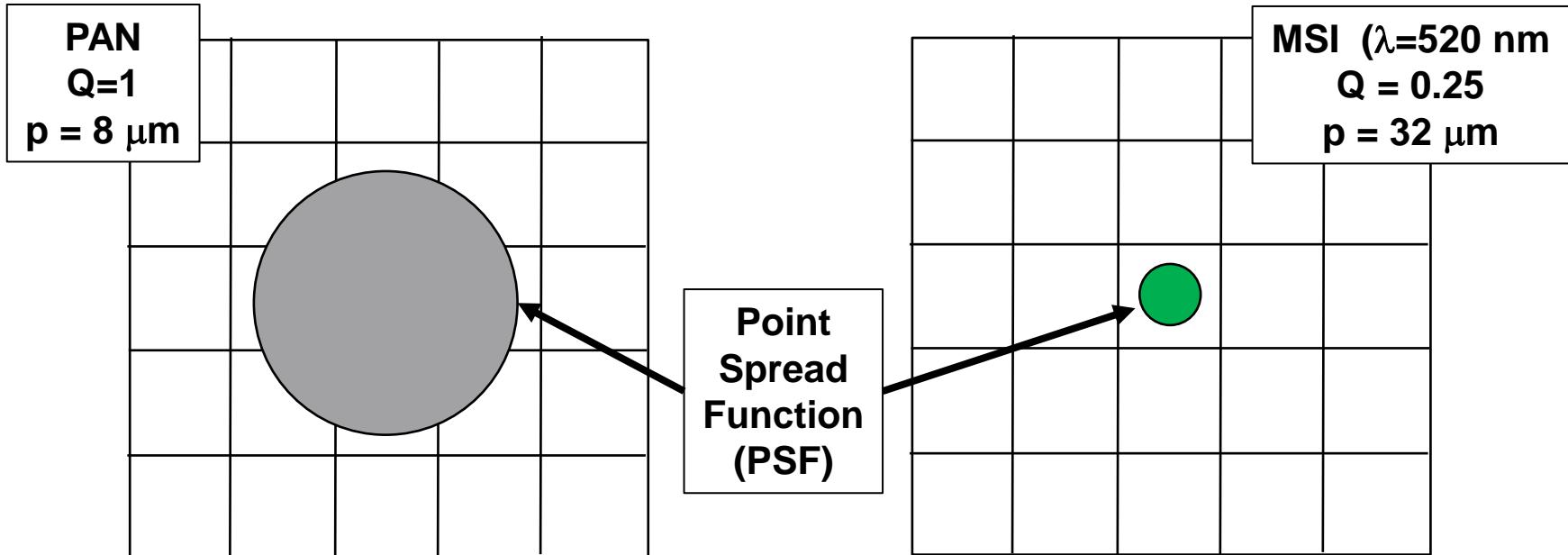


Improving Spatial Resolution at Fixed GSD and Q< 2.0

- **Oversampling** – increasing the effective Q by increasing line rate
 - $LR = (V_{ss}/GSD) \times n$, where $n > 1$ (V_{ss} is the sub-satellite velocity)
 - For 1m GSD, $LR \approx 7000$ lines/sec
 - Examples: EROS-B (ISR) and Pleiades (FRA)
- **Super-Resolution** – a class of techniques to enhance resolution
 - Optical SR can overcome the diffraction limits in Fourier optics
 - Geometrical SR superimposes multiple exposures of images
- **Implications for NOAA regulation**
 - Core regulatory authority is over “operational capability”
 - **Oversampling** in satellite RS systems requires a specific “operational” mode related to line rate and possibly back-scanning
 - **Super-resolution** in satellite RS is a different “operational” mode, often related to dithering a 2-D camera pointing axis
 - Licenses could explicitly limit the use of either mode to improve the ability (CDP or customer) to improve “effective” GSD licensing thresholds



Spectral Imaging: the Impact of “Q” on MSI/HSI



- PAN systems are designed to sample the PSF in multiple pixels
- MSI/HSI systems should constrain the PSF for spectral bands to 1 pixel
 - *The pixel location of a “point source of color” should be unambiguous*
 - *Larger pixels also produce greater SNR ($S \propto Q^{-2}$)*
- Co-boresighted PAN/MSI systems differ in IFOV and therefore GSD, but...
 - *Additional utility can be derived from PAN-sharpened MSI images*
 - *PAN-sharpening is different from advanced spectral-spatial analysis*



Implications for NOAA/NASA RS Satellites

Technology Transfer and Export Review

- Technology versus image quality
 - $Q = (\lambda \times FN)/p = (\lambda \times L)/(D \times p)$
 - $p/L = IFOV = \lambda / (Q \times D)$

VNIR Panchromatic														
Aperture D(m)	$\lambda_{\text{mean}} (\mu\text{m})$	Pixel Pitch p(μm)	Focal Length L(m)	Q ($\lambda \times FN/p$)	IFOV (μrad)	H (km)	350	400	450	500	550	600	650	700
0.70	0.675	8.00	6.64	0.8	1.21		0.42	0.48	0.54	0.60	0.66	0.72	0.78	0.84
0.70	0.675	8.00	8.30	1	0.96		0.34	0.39	0.43	0.48	0.53	0.58	0.63	0.68
0.70	0.675	8.00	9.96	1.2	0.80		0.28	0.32	0.36	0.40	0.44	0.48	0.52	0.56
0.70	0.675	8.00	11.61	1.4	0.69		0.24	0.28	0.31	0.34	0.38	0.41	0.45	0.48

VNIR/SWIR Hyperspectral														
Aperture D(m)	$\lambda_{\text{mean}} (\mu\text{m})$	Pixel Pitch p(μm)	Focal Length L(m)	Q ($\lambda \times FN/p$)	IFOV (μrad)	H (km)	350	400	450	500	550	600	650	700
0.70	0.40	25.00	2.80	0.064	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	0.60	25.00	2.80	0.096	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	0.80	25.00	2.80	0.128	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	1.00	25.00	2.80	0.160	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	1.50	25.00	2.80	0.240	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	2.00	25.00	2.80	0.320	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25
0.70	2.50	25.00	2.80	0.400	8.93		3.13	3.57	4.02	4.46	4.91	5.36	5.80	6.25

GSD = IFOV x H = constant at a given H for hyperspectral



In Summary

Definitions:

$$GRD = 1.22 \times (\lambda/D) \times H$$

$$GSD = (p/L) \times H = IFOV \times H$$

$$IFOV = p/L = \lambda/(QxD), Q = (\lambda \times FN)/p$$

- **Aperture constrains best possible spatial resolution for satellite imagers**
 - Single band systems (VNIR, SWIR, MWIR, LWIR) are optimized for spatial resolution, aliasing reduction, and SNR
 - Best resolution attainable for high-resolution PAN largely determined by system GRD (i.e., aperture)
- **Spectrally-resolved systems (MSI, SSI, HSI) constrain spatial sampling to a single pixel using $Q \ll 1$**
 - Effective resolution is often determined by GSD alone
 - Instantaneous Field-of-View (IFOV) is a useful intrinsic sensor metric
 - Regulators would be wise to use IFOV to inform export evaluation of large aperture spectrally-resolved systems (e.g., meteorological sensors)



Back-Up

